WCRP REPORT

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CLIVAR

Project Report

Report of the 1st workshop of CLIVAR research focus CONCEPT-HEAT

29.09.-01.10.2015 at Met Office, Exeter, UK.

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1. Content

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"Understanding the flow of energy through the Earth system is one of the most important issues for climate science. The two most fundamental, and related, questions to address are: "where is the heat going?" and "where is the water going?" The recent pause in global surface temperature warming has highlighted the need to understand where heat is going in the ocean. We also know that the movement of water through evaporation, clouds and precipitation are fundamental to life and to the Earth's energy budget."

Julia Slingo; UK Met Office Chief Scientist

General background. Climate is the result of energy transfer between the different components of the Earth's system. The Earth's Energy Imbalance (EEI) is the most fundamental measure of climate variability and the rate of global change (Hansen et al., 2011; von Schuckmann et al., 2015). All the energy that enters or leaves the climate system radiatively at the top of Earth's atmosphere is balanced under an equilibrium climate. Any climate forcing (of natural or anthropogenic origin) can perturb this energy balance and give rise to EEI, i.e. excess of energy – mostly in the form of heat – in the climate system.

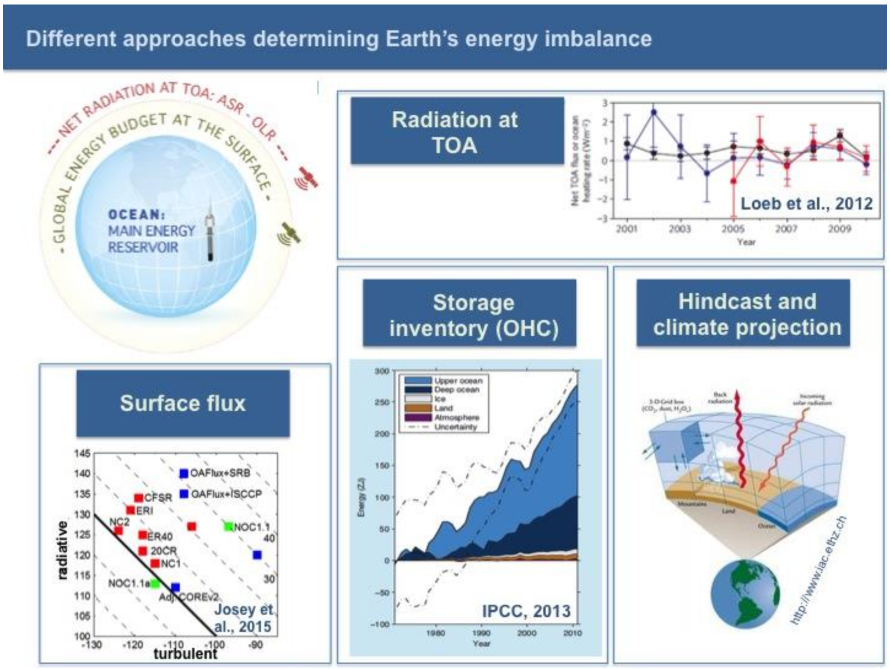

Figure 1: *Schematic presentation of different approaches that are used to estimate Earth's energy imbalance (EEI). Values of EEI can be derived from: i) remote sensing at the Top of the Atmosphere (TOA); ii) the mean ocean surface budget as derived from in situ observations, remote sensing data and atmospheric reanalyses; iii) an inventory of heat stored in the climate system – in particular in the global ocean from in situ measurements and ocean reanalyses systems – and iv) from state-of-the-art numerical model approaches.*

There are four approaches that can potentially be used to estimate the absolute value of EEI and its time-evolution (Figure 1). An overarching scientific challenge faced by the whole climate science community is related to the fact that each method has its own strengths and weaknesses, however in many ways, the various methods are complementary (von Schuckmann et al., 2015). Addressing this challenge is the primary objective of the CLIVAR research focus CONCEPT-HEAT (Consistency between planetary energy balance and ocean heat storage). Developing the knowledge, and observational capability, necessary to "track" the energy flows through the climate system is critical for improved understanding of the relationships between climate forcings, the Earth system responses, climate variability and future climate change.

Objectives of CONCEPT-HEAT and the workshop. CONCEPT-HEAT aims to bring together experts from ocean and atmospheric reanalysis, air-sea fluxes, ocean heat content (OHC), climate models, atmospheric radiation and sea level to better synthesize all the information available. Thus, an important goal of our workshop was to foster collaboration among these different communities and begin to build up a multi-disciplinary synergy community to promote progress on two central tasks:

I. Quantify Earth's energy imbalance, the ocean heat budget, and atmosphere-ocean turbulent and radiative heat fluxes, their observational uncertainty, and their variability for a range of time and space scales using different observing strategies (e.g., in-situ, satellite), reanalysis systems, and climate models.

II. Analyze the consistency between the satellite-based planetary heat balance and ocean heat storage estimates, using data sets and information products from global observing systems (remote sensing and in situ) and ocean reanalysis. In addition, the results can be used to compare to outputs from climate models to facilitate validation.

Workshop organization and participants. The workshop took place over 3 days (Fig. 2). The first 2 days were allocated to the presentation and discussion of new scientific results under four different main CONCEPT-HEAT topics, i.e.

- The Earth's energy budget
- Energy flows as estimated from reanalyses and climate models
- Air-Sea fluxes
- OHC and atmospheric radiation

Day 3 was dedicated to a plenary discussion on "Consistency between planetary energy balance and ocean heat storage". The workshop had participation from 41 multi-disciplinary experts from 14 different countries. A senior editor from "*Nature*" also attended the first two days of the workshop. A detailed list of participants is available from the CONCEPT-HEAT webpage: http://www.clivar.org/events/workshop-energy-flow-through-climate-system.

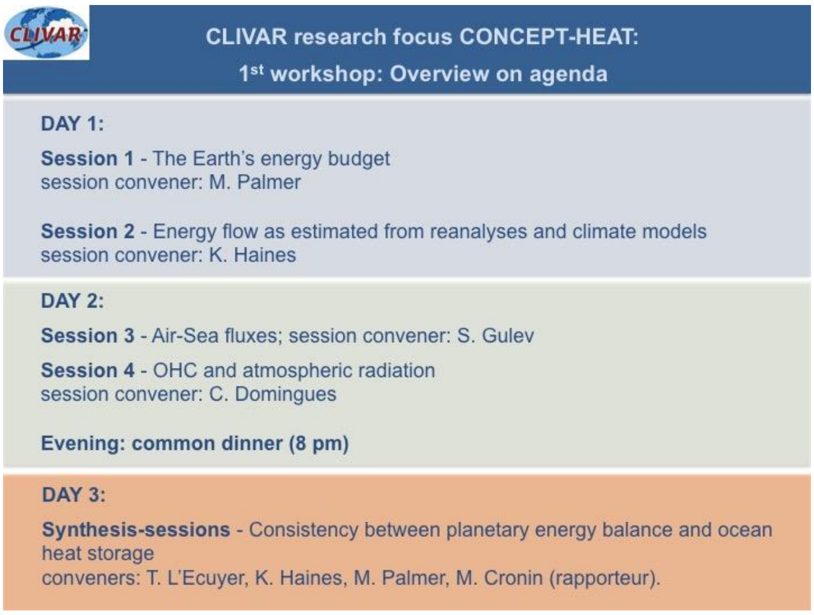

Figure 2: *Overview on program of the 1st CONCEPT-HEAT workshop (29.09.-01.10.2015, Met Office, Exeter, UK). The detailed program, session chairs and a list of attendees can be found in the appendix (2&3), and presentations can be downloaded from the CONCEPT-HEAT webpage: http://www.clivar.org/events/workshop-energy-flow-through-climate-system.*

Workshop outcomes on "Consistency between planetary energy balance and ocean heat storage".

1. Earth's Energy Imbalance.

The most fundamental measure that climate is changing is the Earth's Energy Imbalance (EEI, von Schuckmann et al, 2015). Assessing the status of global climate change, improving climate syntheses and models, and testing the effectiveness of mitigation actions can be improved through a reliable estimate of the EEI, currently estimated to be on the order of 0.5-1.0 W m^{-2} over the surface area of the Earth (IPCC, 2013). Combining multiple climate measurements and tools in an optimal way holds considerable promise for estimating EEI and to narrow its uncertainties. A reliable estimate of EEI is most robustly determined through taking an inventory of where all of the Earth System energy change is occurring. The main repository is the ocean from ocean heat content (OHC), where about 93% of the increase in energy results, while small amounts go into melting sea ice, land ice (glaciers and ice sheets), and warming the land and atmosphere (Trenberth 2009; Hansen et al. 2011; IPCC 2013). Top of the atmosphere (TOA) changes in EEI over time from remote sensing techniques are claimed to be reliable to within 0.3 W m^{-2} per decade (Loeb et al. 2009), but absolute values are uncertain. EEI as obtained from climate models depends on how good the model and the forcing are. The largest uncertainties are related to atmospheric reanalysis (remaining challenges in forcing energy conservation) and large systematic errors in the surface flux budget (up to 20 W m^{-2}). However, progress has been and can be achieved with a concerted international effort, in particular through the development of a CONCEPT-HEAT synergy community.

1.1 Regional distribution of EEI

There are multiple sources of information that can be brought to bear on estimates of EEI. As well as global estimates, it is desirable to have the energy imbalance locally and as a function of time of year. There is a framing for how to do this related to what has previously been called a "CAGE" experiment envisaged in the early 1980s (Bretherton et al. 1982; Yu et al., 2012; WCRP, 2013). The design of the CAGE experiment recognized:

(i) the importance of meridional heat transport in Earth's climate,
(ii) the need for obtaining an accurate estimate of the mean state of the global climate and of the ocean's role in maintaining that state,
(iii) uncertainties in existing surface flux products and ocean observations that preclude realistic assessment of the changes in ocean heat transport and storage.

Three approaches for computing meridional heat transport by the oceans were proposed, including using the ocean temperature and velocity observations, air–sea heat fluxes, and the net radiation at the top of the atmosphere coupled with the atmospheric flux divergence. The CAGE experiment was designed to inter-compare the three types of product in a single basin under favorable circumstances to establish the random and systematic errors associated with each approach, and hence to determine the changes in ocean heat storage. The region of the north Atlantic 20°N–60°N was recommended to attempt the use of the Bryden and Hall (1980) assumption on long coast-to-coast zonal sections every 5-degrees from 24 to 60°N.

It is now possible to carry out this approach owing to numerous advances in the global climate observing system. Observations of variations in TOA radiation exist since March 2000 from the NASA CERES mission (http://ceres.larc.nasa.gov/). This information can be combined with improved estimates of the atmospheric energy divergence from reanalyses to estimate the net air-sea heat fluxes (e.g. Liu et al., 2015). Estimates of upper ocean OHC can be more accurately determined from Argo after about the year 2005 for the 0–2000m depth layer (von Schuckmann et al., 2014; Roemmich et al., 2015) and for the full depth from the residual of satellite sea-surface height and ocean mass data after 2002 (e.g. Dieng et al., 2016). Ocean reanalysis and synthesis are available for heat transport divergence estimations (Balmaseda et al., 2015). The quality and quantity of surface flux products has been increased (e.g., under GEWEX), and improved uncertainty estimates are under the way (e.g. www.oceanheatflux.org). Putting these ingredients together, energy budgets can be done locally with useful uncertainty estimates, which may enable regional budget closure. In addition, other constraints such as from choke points or special observations (e.g., the Rapid array, see examples by Cunningham et al., 2013; Bryden et al., 2014) can be used to further understand uncertainty limits of this approach. Reconciling TOA plus atmospheric results with surface fluxes, and in turn with ocean heat budgets, plus closure for the entire system are key goals of CONCEPT-HEAT. Focused projects on certain times and phenomena may be insightful (annual cycle, ENSO, changes from 2006 to 2014) as well as building understanding of the strengths and weaknesses of the various datasets on different timescales. Sub-projects may occur on inter-comparisons of various estimates for regional dOHC/dt; surface fluxes from multiple sources (ocean reanalyses, atmospheric reanalyses, seaflux, OAflux, NOC, etc) and direct flux measurements; MIPs, etc.

1.2 The estimation of OHC plays a key role for climate science

The different discussions (of sessions 1-4, and synthesis) reached one overarching consensus, highlighting the importance that the estimation of OHC plays a key role to overcome challenges in climate science. Different communities and research tasks would all benefit from an improvement of estimates of OHC and its rate of change (d(OHC)/dt), in particular:

i) Climate monitoring (state and variability): The absolute value of EEI represents the most fundamental metric defining the status of global climate change. It is dominated by and can best be estimated from d(OHC)/dt complemented by radiation measurements from space (von Schuckmann et al., 2015), with small additional contributions from other climate system components.

ii) The TOA net flux from remote sensing requires calibration from the energy inventory terms (Loeb et al., 2012).

iii) For taking an inventory of where all of the accumulated energy change is occurring, OHC is dominant on interannual to centennial timescales (IPCC, 2013).

iv) OHC and the related thermal expansion is an essential element for improving estimates of global and regional sea level rates (e.g. Church et al., 2011).

v) OHC changes come about through both air-sea heat fluxes and ocean dynamics and the breakdown between the two is essential for better understanding energy flows in climate modes (ENSO, PDO, NAO, …) and their predictability.

vi) OHC is a fundamental variable for climate modeling assessment and there is a large potential to reduce model errors through consideration of:
   - EEI diagnostics
   - Climate response functions
   - Analysis of the process fingerprints of OHC changes associated with major climate modes (ENSO, PDO, NAO, …)

vii) Changes in OHC have direct implications for surface flux products, including those from remote sensing, through regional ocean energy budget constraints (section 1.1).

1.2.1 Improved ocean observation system. There is a requirement for high quality observational ocean products with well-quantified uncertainties (GCOS, http://www.gcos-science.org/pg/Register.aspx). Already tremendous improvements have occurred for global OHC estimates, in particular due to the global Argo array. Moreover, extensive analyses have been performed to discuss and identify the strengths and weaknesses of the global ocean observing system for climate research applications. These results are fundamental, and identify key issues of how the global ocean observing system needs to be complemented to improve global OHC estimates (note that extensive efforts are under the way to foster these developments including technological developments such as deep floats, under ice techniques, etc). These include:

- the deep ocean (Trenberth and Fasullo, 2010; Balmaseda et al., 2013; Purkey and Johnson, 2010; http://www.argo.ucsd.edu/AcDeep_Argo_Workshop.html);
- marginal seas (von Schuckmann et al., 2014);
- polar regions (SOOS, www.soos.aq)
- the near surface layer (upper 10m, Trenberth et al., 2014a).

1.2.2 Improve OHC estimate capability. OHC is analyzed by a number of institutions, and uncertainty estimates and sources have been addressed and discussed in several studies (e.g., Lyman et al., 2010; Abraham et al., 2013; Cheng et al., 2015; Boyer et al., 2016). In particular, gap-filling in space and time remains a key issue, as does the representativeness of individual profile measurements owing to ocean eddies. 4D ocean data assimilation (DA) using ocean reanalysis should provide the most comprehensive way to gap fill in both space and time, but model bias remains an issue. By providing a focus on dOHC/dt, new characteristics of OHC would be revealed related to continuity, and whether values are physically realistic. OHC changes because of ocean dynamics, and hence grappling with ocean heat transport divergence in a column or layer is also a necessary research task.

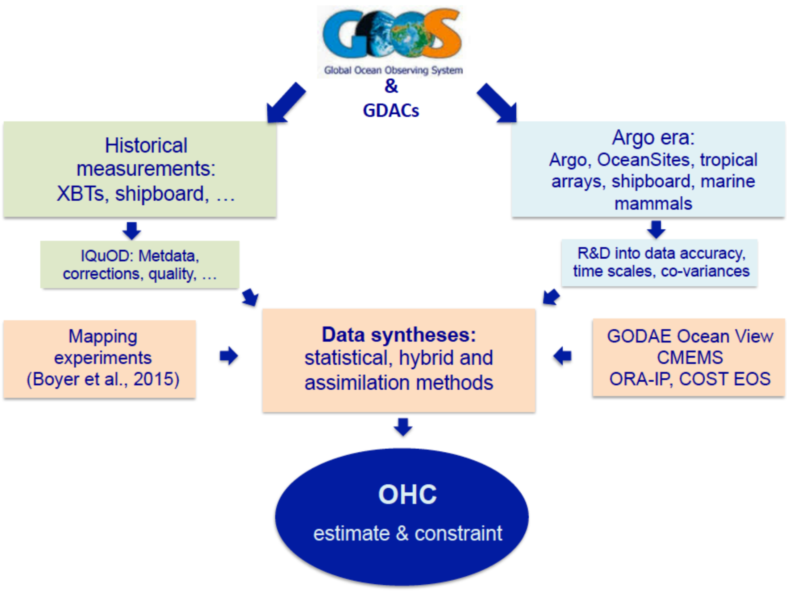

Fig. 3: *Framework for planned activities on OHC estimates, which had been developed during the workshop. The aim is to use this schematic representation to further refine and update OHC and related uncertainties under CONCEPT-HEAT.*

1.3 Increase understanding of energy flows in climate modes

There are indications, such as from Balmaseda et al. (2013), that the vertical disposition of heat in the ocean varies, in particular with various modes of variability such as the PDO (Trenberth and Fasullo 2013; England et al. 2014; Roberts et al., 2015) and ENSO (Mayer et al. 2014; 2015). This had earlier been found in a climate model (Meehl et al., 2011; 2013) where mechanisms and processes can be documented more readily. During the so-called hiatus period from 1999 to 2013, when there was a negative phase of the PDO, there are major changes in surface winds that bring about systematic changes in ocean currents and overturning. In particular, in the Pacific, subtropical overturning redistributes heat vertically in the upper 700 m or so. However, teleconnections to other ocean basins occur (e.g. Indian Ocean, Lee et al., 2015; to the North Atlantic and Southern Oceans, Trenberth et al., 2014b) and enable deeper exchanges to occur, presumably in conjunction with changes in ocean convection that are important seasonally (Trenberth et al., 2014b). Chen and Tung (2014) speculate on alternative mechanisms, and other modes of variability, notably the North Atlantic Oscillation likely also plays a role.

These studies and findings highlight the need to better understand the modes of natural variability in terms of how they affect flows and storage of energy.

2. Research activities to develop components of EEI

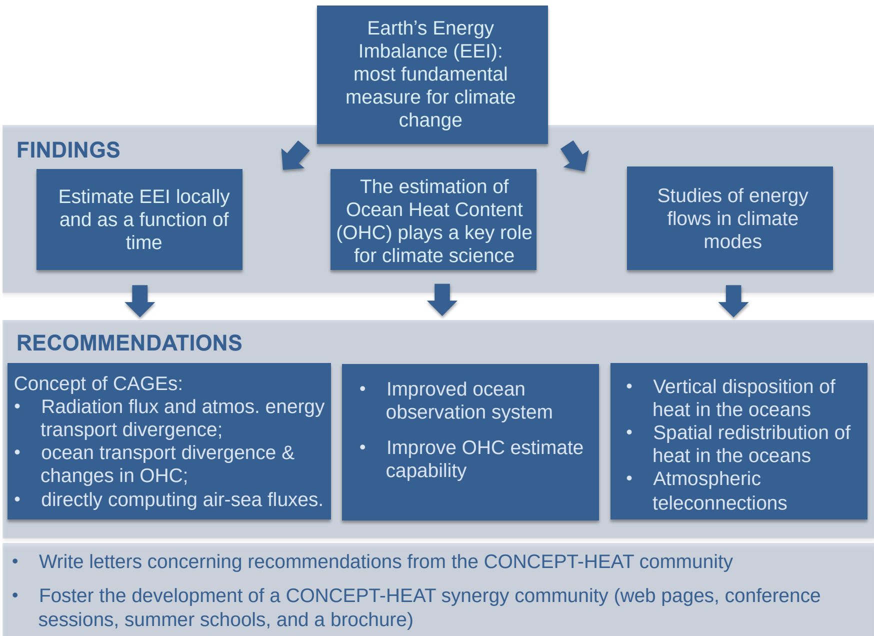

Figure 4: Overview on principal findings and CONCEPT-HEAT recommendations from the workshop. See text for more details.

2.1 Regional analyses of EEI

2.1.1 Development of "CAGE" experiments

Three main ways exist to obtain air-sea fluxes:
1. implied from TOA flux and atmospheric energy transport divergence;
2. implied from ocean transport divergence and changes in OHC;
3. assembling net fluxes from estimates of the flux components.

The main consensus reached within the discussion is that we need to validate transports in both atmosphere and ocean (regionally and zonally), predominantly from synthesis products (the validation procedure will in turn identify outlier synthesis products). The best period window of most complete ocean data is the post-2005 period (e.g. 2008-2010); i.e. when Argo sampling reached its initial target of 3000 floats with near-global sampling, and flux products are available (many products are available up until 2010/2012). The dates can be extended as confidence grows in the more recent products. The CONCEPT-HEAT recommendations for research activities are:

- Establish focus groups to design and perform inter-comparison initiatives of component products.
- Identify weaknesses related to uncertainties, product biases, sampling (in situ) and resolution (remote sensing).
- Develop common metrics with uncertainty estimates.
- In addition to climatology energy flows, consider also the seasonal cycle, flux anomalies and with a focus on climate modes and regional variability.
- Deliver standardized ocean heat divergence at regular (e.g., 5 degree or less) latitude bins from ocean reanalyses during a specified period (i.e., post-Argo as specified above).
- Marginal seas also offer the opportunity for CAGE experiments, but Marginal Sea community might be in need of high-level support.
- Option to connect with Large Marine Ecosystem groups (e.g., ASCLME)
- Support to science elements from ESA: Ocean Heat Flux (OHF) consolidated data base (www.oceanheatflux.org)

Identified challenges:
  - Need to promote funding initiatives.
  - Might not be possible to get these high-level diagnostics (derivatives, fluxes, transport divergences,…) from anything other than reanalyses, 4dvar state estimates.

2.1.2 Earth energy budget closure

A particular project underway, related to CAGEs, led by NCAR, is to use the TOA radiation from CERES plus the atmospheric reanalyses to compute the vertically-integrated energy transports and their divergence, and thereby compute monthly surface net heat fluxes as a residual. By combining these with analyses of OHC, the implied divergent component of the ocean heat transports can be computed as a residual. By using certain choke point estimates, such as the Bering Strait and Indonesian Throughflow, the divergent component of the ocean heat transports can be computed and compared with estimated values from instrumented arrays such as the Rapid array. In turn this provides a target for the surface flux products and ocean reanalyses to examine their fluxes, transports and dynamics. This also provides a backdrop for examining closure of regional heat budgets (see also ongoing activities under NERC DEEP-C project, http://www.met.reading.ac.uk/~sgs02rpa/research/DEEP-C.html).

It is expected that this project will become a core CONCEPT HEAT project that involves all communities to better understand and track energy flows through the climate system and help evaluate the accuracy and utility of various products and models. It should lead to intercomparisons, weighted toward the Argo period, and assessments using physical budget constraints (sea level budget, Earth's energy budget) and thus cross-validation/assessment of independent global climate observing systems; with links to operational services.

As well as focusing on fluxes, which requires d(OHC)/dt, an alternative approach is to integrate the fluxes in time (TOA and surface) and compare with OHC, to highlight the lower frequencies. There is merit in sorting out the annual cycle, interannual variability (ENSO etc), and lower frequencies. The observational results also set the stage for model intercomparison project (MIPs) and thus model improvements.

2.2 Improvement of OHC estimates

Based on the current the framework and activities for OHC estimates (Fig. 3), the following recommendations for research activities have been agreed and aiming at addressing this question: "Why do d(OHC)/dt give such different values?" Clearly some of this is because of noise that is a function of time-scale (e.g., monthly vs annual).

- Use d(OHC)/dt from Argo, RA and climate models and assess consistency in space and time.
- Obtain relative importance of currently under-sampled regions for estimating contribution to net TOA from d(OHC)/dt and use models/ORAs to understand the subsampling problem – both time and space.
- Support more in-depth evaluation of the different estimates such as the development of "synthetic profiles" from model simulations to test mapping methods, or approaches and inter-comparisons to test different XBT correction methods. Several activities are under the way (e.g., Boyer et al. (2016), IAP/CAS (L. Cheng et al.): mapping methods evaluation using observational proxy (talk of workshop); CSIRO/Met Office/ IMAS/UTAS, ACE CRC, ARCCSS (J. Church; D. Monselesan; M. Palmer; C. Domingues): evaluation of mapping methods using model outputs). The CONCEPT-HEAT webpage could deliver a platform to join and summarize different activities.
- Inter-comparison initiatives for uncertainty assessments, utilize reference sites.
- Consider independent measurements from remote sensing (SST, SSH, validation through sea level budget).
- Establish links between different programs/initiatives (e.g., deep Argo, OceanSites, GO-SHIP, …)
- Evaluate consistency between CERES and d(OHC)/dt over the annual cycle.
- "Benchmarking" of Argo period – consistent time series for OHC time series (global scale, and for regional budget constraints): Develop framework to assure "climate quality" for global and regional (regional budget constraints frame work) mean OHC estimates, and to understand current differences in these estimates from different research groups (see for example Figure 4b von Schuckmann et al., 2015).

2.3 Energy flows associated with major climate modes (GSOP/CONCEPT-HEAT)

One important objective identified is the analysis of the redistribution of heat in climate modes (ENSO, PDO, NAO, etc.) using climate models and reanalysis systems to characterize these exchanges, and further understand where the heat is going (e.g., Mayer et al. 2015). There is also a potential to analyze climate variability to characterize OHC exchanges and identify their monitoring potential in observations (reanalyses) and models.

A particular emphasis has been highlighted to understand “how consistent are the synthesis products in depicting where the upper ocean heat got into the deeper ocean during the recent staircase warming period from 1999 onwards?” More precisely:

- For the global ocean, how much heat in the upper ocean got into the deeper ocean? (say across 300 m or 700 m)
- Which are the key regions for these vertical re-arrangements of heat (beside from tropical Pacific)?
- What is the contribution of the North Atlantic or other regions (e.g. Chen and Tung 2014)? What about the transfer of heat content from the Pacific to the Indian Ocean (e.g., Nieves et al. (2015) and the model/reanalysis by S. Li)?
- What happen to the surface heat flux trend during the hiatus period?

In particular, this research activity was commonly discussed between GSOP and CONCEPT-HEAT. The ocean heat content files from the ORA-IP initiative will be put into the Easy Init catalogue of the Hamburg server (http://icdc.zmaw.de/projekte/easy-init/easy-init-ocean.html) along with other fields for ORA-IP, such as ocean synthesis derived surface heat flux products. These research topics can be analyzed from reanalyses and observational fields, which in turn can be assessed on their consistency.

3. Develop letters of recommendations from the CONCEPT-HEAT community

- Letter to OceanSITES, cc to CLIVAR, GDACs (NDBC and Coriolis) for making fluxes components available (not just state variables) in easy to use format, preferably one-stop-shop (Lead: Megan Cronin, TbC).
- Letters to RA groups to withhold KEO & Papa from RA. Also to make list of what data are used (Lead: Magdalena Balmaseda, TbC).
- Withholding OceanSITES data from future atmospheric re-analyses, since they are key for validation: letter to the group involved in the new ECMWF reanalysis effort encouraging them to withhold OceanSITES data with WMO #s indicating the site is a reference site. This specifically is the case for KEO (WMO #=OLD: 28401, NEW: 2800401) and Papa (WMO #=OLD: 48400, NEW: 4800400). The "84" in the old format and "8004" in the new format indicates it is a reference site. In general, operational models want to assimilate ALL data. Life and property depend upon getting the most realistic fields. However, for the reanalyses, it would be extremely beneficial to have these reference data for intercomparisons. At the very least, it would be very helpful to know exactly what is assimilated (variable and site) so that when doing these intercomparisons we know if the data are independent or not (Lead: TbD).
- Letter to Atm RA to pay attention to TOA radiation and forcings for climate studies (Lead: Kevin Trenberth)
- Letter to Argo about intercomparison of methods using Synthetic dataset, intercomparison of existing gridded datasets, regular monitoring of budgets for quality monitoring. Also give model groups this synthetic dataset (Lead: Karina von Schuckmann, Matt Palmer).

- Letter to program managers/countries, with copy of this report, to increase funding for EEI studies (Lead: Karina von Schuckmann, Kevin Trenberth)
- Letter to CMIP6 to encourage host/partner institutions to save the d/dt diagnostics that are needed to close global and local OHC budgets (e.g. this will be done for a subset of models under FAFMIP) (Lead: Matt Palmer)

4. Further foster the development of a CONCEPT-HEAT synergy community

- Priority: CONCEPT-HEAT webpage, which should be the anchor of community and information exchange for all concerned with energy flow through the climate system. Besides an overview on background and objectives of CONCEPT-HEAT (and distribution of related documents), this webpage is planned to deliver a regular up-dates on related science results, calendar on meetings and workshops in related fields, overview on research structure and projects, regular news-letters, as well as an interactive platform (to be defined). Funding for the development and implementation is proposed from IORAS (Russia), the hosting of the web-page is assured through Tasmanian Partnership for Advances Computing (TPAC), University of Tasmania (Australia), and maintenance is proposed through IAP (China). Once the funding is assured for the development, a first draft is planned for January 2016.
- Summer school: Several opportunities were suggested: Funding through COST EOS, or development of a NCAR ASP proposal, or US CLIVAR proposal; or Grenoble (France, in January: negotiate to be from TOA to bottom of ocean flux which would be broader than their normal topics)
- Conference sessions:
  - CLIVAR Open science conference in China in September (Energy session chaired by K. von Schuckmann and J. Gregory). Abstracts due in March 2016. Should coordinated abstracts be submitted?
  - WCRP conference? WCRP Sea level Grand Challenge Conference in NY 2017. One session will be OHC.
  - AGU 2017 or AMS session?
  - Calendar of Conference/workshops on CONCEPT-HEAT website will further support this coordination task
- Develop a brochure to summarize and promote CONCEPT-HEAT activity: This brochure is already in development thanks to support of IORAS (Russia), including a summary of CONCEPT-HEAT and statements of different representatives from IOC, ESA, Met Office, … Action here is to refine this draft, mainly within the CONCEPT-HEAT steering team.

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Appendix 1: Summary of discussions

Some questions arising:
How can we improve validation requirements for and from climate models and reanalyses to improve system?

- Requires high quality observational products with clear but narrow uncertainties.

Climate models: How fast can heat move down in the ocean and where and how deep?

- Versus observations and/or reanalyses. Role of convection, mixing and dynamics

Is EEI from natural variability (e.g. hiatus events) or forced variability (e.g. volcanoes, GH)?

- There is large EEI monthly from weather (clouds), interannual (ENSO etc), and decadal (PDO etc)

Do climate models redistribute heat correctly in ENSO, PDO, NAO events?

- Requires good data/analyses and appropriate studies to document this in real world and models.

Radiative relations (SW, LW covariability)?

- There is large local compensation between ASR and OLR via clouds of all sorts, but a tremendous amount cancels when globally averaged, implying that it relates to weather systems and waves.

Horizontal redistribution eg. ENSO Ht rearrangements

- The atmosphere moves tremendous amounts of heat around, so that surface fluxes do not relate well to TOA fluxes; but so too ocean currents move heat around, and anomalously during ENSO etc.

Any systematic effects on energy redistribution from resolution?

- There remain uncertainties in TOA radiation from diurnal and sampling effects; Argo also aliases ocean eddies, and atmospheric divergence degrades at small scales. Some of these effects cancel simply by area averaging, but resolution in space and time remains an issue.

CMIP6 diagnostics availability for EEI?

- Are all the requisite fields archived, and are there projects to assess EEI locally and globally? => develop recommendation to encourage host/partner institutions to save the d/dt diagnostics that are needed to close global and local OHC budgets (e.g. this will be done for a subset of models under FAFMIP)

Are some MIPs also relevant to EEI monitoring or change quantification?
How can reanalyses be improved?

- Reanalyses tend to move sequentially forward in time, thus from poor data times to much better data, especially in the ocean. It is essential to utilize the bias corrections and covariances from data-rich periods throughout the record, although this may involve assumptions about stationarity, and conditional values may be desirable (whether or not there is an El Niño, sign of PDO, etc). Iterative methods may work.
- Or are there alternatives to 4DVar?
- In the ocean there is a large annual cycle of heat uptake and release. This means care is required for defining anomalies.

How can we capitalize on the multiple methods of assessing EEI? The surface fluxes can be computed from a combination of:

- TOA radiation plus atmospheric divergence and tendency
- In situ surface flux computations using bulk formulae
- Satellite based surface fluxes (SEAFLUX, LANDFLUX)

- From atmospheric reanalyses
- From ocean reanalyses (adjusted surface fluxes from model)
- From changes in OHC and ocean divergence. (Latter might be from reanalyses).

Many of these can be done locally but many improve as area averages are taken, (e.g. over ocean basins with natural boundaries that limit ocean transports), and this leads to the idea of CAGE experiments.

Recommendations for activities:

- Use d(OHC)/dt. From Argo, RA and climate models. Consistency in space and time?
- Deliver ocean heat divergence? Standardise? 10 degree bins? Specified period. Needs sfc fluxes applied to products. Ocean heat divergence for zones across oceans would enable meridional ocean heat transports by the ocean to be computed.
- Data repository for ORA-IP products to allow further study.
- Further studies of energy flows in climate modes, ENSO etc. to characterize exchanges.
- Establish reference sites, regions where OHC / sfc fluxes reliable (CAGES?) – test multi products against these. Can the heat and fresh water budgets be closed at these sites?
- Agree on data needs from CMIP6 for EEI studies.
- Climate variability EOFs to characterize heat content exchanges and monitoring potential?
- Establish links between different programs, e.g. GO-SHIP, etc.

Appendix 2: Workshop agenda

Agenda: Workshop CONCEPT-HEAT

The workshop will be organized in four different sessions, which are aiming to centralize main outcomes at the forefront of climate science as well as to highlight main challenges:

Session 1: The Earth's energy budget

Each of the existing independent approaches (satellite measurements at TOA, in-situ observations and reanalysis outputs for ocean heat content, estimates of EEI from climate models) to determine values for energy flows in the Earth's system has its own advantages and drawbacks in terms of sampling capability and accuracy, leading to different estimates, and associated uncertainties. In addition different communities are involved in delivering these estimates and as yet these communities have not worked closely together to allow different assumptions to be compared and for some of the uncertainties to be reduced. Thus evaluating and reconciling the resulting budget imbalance is a key emerging research topic in climate science, which has the potential to bring different communities together to make a major contribution to reducing climate change uncertainties. Errors involved in deriving single components without a coupled context can accumulate and have major impacts on the accuracy of climate indicators, leading to large imbalances differences in estimates of Earth's budgets and climate. Reconciling the different approaches remains a challenge. This session explores our capability to measure and understand the exchanges of energy in the Earth's climate system, in particular in the quantification of the magnitude and spatial distribution of heating in the system, and will hence give the introduction and background to our workshop. The principal scientific question will be

“What is the magnitude and the uncertainties of our estimates of Earth's energy imbalance (EEI), and how does it vary over time?”

Session 2: Energy flow as estimated from reanalyses and climate models

We need to further understand the role of resolution of climate models and reanalysis models in resolving natural climate variability and providing accurate error estimates, as well as to understand which are the relevant model physics and parameterizations that need further improvements. The combination of ocean models, atmospheric forcing fluxes and ocean observations via data assimilation methods has the potential to provide more accurate information than observation-only or model-only estimations. This session principally builds on the outcomes of the initiative ORA-IP, as well as from experts of COST-EOS dedicated to focus on main outcomes, achievements, and remaining challenges of estimating energy flows through (and storage) the climate system from this climate tool. Of particular focus will be outcomes for OHC. Addressing the energy budget in climate models is a powerful method for understanding future climate projections. A prerequisite thereby is an adequate representation of the energy budget in climate models, which requires a careful validation process and adequate reference datasets. This session is hence dedicated to address the following scientific question: “How can we improve validation requirements for and from climate models and reanalysis systems to improve estimates of EEI?”

Session 3: Air-sea fluxes

Characterizing the uncertainty and biases in surface fluxes is essential to address scientific challenges related to the Earth Energy budget, energy flows and understanding the observed interannual to interdecadal variability superimposed on the centennial-scale warming of the global ocean surface. Quantifying sea surface heat fluxes to the required level of accuracy needed to support the various applications is a very challenging task. The present level of uncertainties in global ocean estimates of heat and moisture fluxes is not adequate for many applications, including global and regional mass and energy budget closure and variability on different time scales. This prevents understanding the mechanisms of ocean climate variability. Biases in surface fluxes lead to the systematic errors in climate models and preclude their efficient use in climate simulation. Without accurate estimates of surface fluxes it is impossible to engage predictive potential of the ocean into weather and climate prediction. Thus, improvements in all aspects of producing surface flux estimates, including parameterizations, measurement techniques and post-processing are required for further progress. This session will hence discuss “How can we better constrain the surface energy fluxes and their spatio-temporal variations at regional scale?”

Session 4: OHC and atmospheric radiation

Observed climate variations such as the current hiatus or unresolved inconsistencies of climate observations (e.g. “missing energy” in the climate system) underpin the need for fundamental research activities on the regional distribution of TOA and OHC (including vertical distribution), as well as their implication for their global estimates. Continued assessment and attribution studies of regional natural climate variability are essential to improve our estimates of global changes. There is also an urgent need to evaluate the relative importance of currently under-sampled regions of ocean heat content change (ice-covered ocean, marginal seas and deep ocean) and to understand how heat is transferred vertically. We have to evaluate how regional patterns change in time and if regional OHC tendency patterns can, along with other patterns e.g. regional sea level, be used to test/falsify model hypotheses. The use of physical budget constraints such as the global sea level budget are an important tool for this evaluation. In summary, this session will address the questions: “How are TOA net radiation and ocean heating rate distributed in space and time?” and “Can consistency between planetary heat balance and ocean heat storage achieved and what are the major limitations?”

AGENDA

Monday, 28th Sep (room C2 1+2): Working session for participants only

13:00-17:00: GSOP meeting (invitation only)
17:00-18:00: joint GSOP/CONCEPT-HEAT meeting (invitation only)

Tuesday, 29th Sep (Conference Rooms 3+4): Open session

8:30-9:00: Registration
9:00-9:20: Welcome and overview on CONCEPT-HEAT (K. von Schuckmann, K. Trenberth)

Session 1 - The Earth’s energy budget; session convener: M. Palmer
9:20-09:50: Keynote: Approaches to addressing the Earth’s energy imbalance (K. Trenberth)

09:50-10:20: Keynote: Surface radiation and energy budget (S. Kato)

10:20-10:50: Keynote: The Earth’s surface budget: Outcomes, uncertainties and drawbacks (L. Yu)

10:50-11:20 Coffee break

11:20-11:40: NASA NEWS energy budget perspectives (T. L’Ecuyer)
11:40-12:00: Energy exchanges between the dynamic components of the climate system: atmosphere and ocean (M. Mayer)
12:00-12:10: Short commentary on session discussion, including key questions for breakout session on Thursday (Session convener)

12:10-14:00: Lunch break

Session 2 - Energy flow as estimated from reanalyses and climate models; session convener: K. Haines
14:00-14:30: Keynote: Climate models: distinctive climate signals and heating of Earth’s climate, and challenges for model validation (M. Palmer)
14:30-14:50: Overview on CMIP6 (C. Senior)
14:50-15:10: Decadal Climate Variability and Predictability (Y. Kushnir, remote talk)
15:10-15:40: Earth's energy imbalance since 1960 in observations and CMIP5 models (D. Smith)
15:40-16:00: Keynote: An overview on ORA-IP (M. Balmaseda)

16:00-16:30: coffee break

16:30-16:50: Improving understanding drivers of ocean-only ocean and coupled near surface ocean biases using a novel heat flux climatology (P. Hyder)
16:50-17:10: Freshwater and heat transports from global ocean synthesis (M. Valdivieso: CANCELLED)
17:10-17:30: Air-sea fluxes from atmospheric reanalysis (R. Allan)

17:30-17:50: Accuracy of global ocean reanalyses (A. Storto)
17:50-18:00: An overview on COST-EOS (K. Haines, A. Alvera Azcarate)
18:00-18:10: Concluding remarks on session discussion, including key questions for breakout session on Thursday (Session convenor)

18h10 End of first day

Wednesday, 30th Sep (Conference Rooms 3+4): Open session

Session 3 – Air-Sea fluxes; session convener: S. Gulev
09:00-09:30: Keynote: Assessing and improving surface flux products across space-time scales: implications for surface energy budget (S. Gulev)
09:30-09:50:Overview on Sea-Flux (C.-A. Clayson)
09:50-10:10: Surface fluxes from in-situ observations and their use in models and parameterizations (S. Josey)
10:10-10:30: Results from inter-comparison of various turbulent heat fluxes (M. Kubota)
10:30-10:50: Air-sea fluxes in the Southern ocean: advancements and challenges (R. Buss de Souza)

10h50-11h10: Coffee break

11:10-11:30: An overview on turbulent flux estimates: current progress and remaining challenges and the ESA-OHF project (A. Bentamy)
11:30-11:40: Concluding remarks on session discussion, including key questions for breakout session on Thursday (Session convener)

Session 4: OHC and atmospheric radiation; session convener: C. Domingues
11:40-12:10: Keynote: Radiation at the Top of the Atmosphere (N. Loeb)
12:10-12:30: Top of atmosphere radiative imbalance: forced trends versus internal variability (A. Donohoe)

12:30-14:00: Lunch break

14:00-14:30: Keynote: A review of global ocean temperature observations: implications for ocean heat content estimates (C. Domingues)
14:30-14:50: Overview on the Argo program, its maintenance and future extensions (B. King)
14:50-15:10: The global ocean observing system: ways to complement Argo (M. Cronin)
15:10-15:30: The ocean's role in Earth's climate change and variability: what have we learned so far from Argo? (K. von Schuckmann)
15:30-15:50: Mechanisms of global and large-scale change ocean heat uptake on multidecadal and longer timescales (J. Gregory)
15:50-16:10: An updated historical (1970-2014) upper ocean heat content estimate and the implication for the global energy budget (L. Cheng)

16:10-16:30: coffee break

16:30-16:50: Climate sensitivity and feedbacks implied by TOA radiation versus temperatures (K. Trenberth)
16:50-17:20: Deep Ocean Warming & Earth's Energy Budget: Observations & Plans (G. Johnson, remote talk)

17:20-17:50: Open comment session, in particular for those without talks (a couple of slides each)
17:50-18:00: Concluding remarks on session discussion, including key questions for breakout session on Thursday (Session convener)

18:00-18:30: Meeting of CONCEPT-HEAT scientific steering team and conveners of breakout session DAY3 (invited)

18h30 End of day 2

20h00: Common dinner

Thursday, 01.10. (Training Room 4): Working session for participants only

Breakout-sessions: Consistency between planetary energy balance and ocean heat storage, conveners: T. L'Ecuyer, K. Haines, M. Palmer, M. Cronin (rapporteur).
09:00-09:40: Summary and outcomes of each session, and introduction into breakout session from conveners
09:40-10:30: General discussion, chaired by session leaders
10:30-11:00: coffee break
11:00-11:30: General discussion, chaired by session leaders. Expected outcome: 15 min. presentation (overview, recommendations, and plans for the future, refinement of key scientific question)
11:30-12:30: Synthesis and commentary by chairs of CONCEPT-HEAT (K. von Schuckmann, K. Trenberth)
12:30-14:00: Lunch break
14:00-16:00: Meeting of CONCEPT-HEAT scientific steering team and conveners of breakout session DAY3 (invited): refine discussion aiming to define common way forward, to foster implementation of synergy community and to foster collaborations, and suggest strategies for funding opportunities. Discussion chaired by CONCEPT-HEAT co-chairs.

16:00 End of workshop

Information on breakout sessions:

Key scientific questions had been developed in the frame of CONCEPT-HEAT white paper, together with recommendations how to move forward for each thematic. The breakout session is aiming to:

i) agree to or refine key scientific questions
ii) refine and complement recommended activities
iii) discuss already existing programs and initiatives, and identify how they could be continued and or improved
iv) identify opportunities for the future
v) develop strategy for each session to join with other sessions
vi) identify opportunities and strategies to foster international collaborations

Below an overview on existing key scientific questions for each session, as well as developed recommendations is given as a basis for developing the breakout sessions. Moreover, a key scientific question for the round table discussions is developed as well, together with recommended activities.

Round table: joining expertise, foster collaborations.

Key scientific question:

Can consistency between planetary heat balance and ocean heat storage achieved and what are the major limitations?

Each of the existing independent approaches (satellite measurements at TOA, in-situ observations and reanalysis outputs for ocean heat content, estimates of EEI from climate models) to determine values for energy flows in the Earth's system has its own advantages and drawbacks in terms of sampling capability and accuracy, leading to different estimates, and associated uncertainties. In addition different communities are involved in delivering these estimates and as yet these communities have not worked closely together to allow different assumptions to be compared and for some of the uncertainties to be reduced. Thus evaluating and reconciling the resulting budget imbalance is a key emerging research topic in climate science which has the potential to bring 6 different communities together to make a major contribution to reducing climate change uncertainties. Errors involved in deriving single components without a coupled context can accumulate and have major impacts on the accuracy of climate indicators, leading to large imbalances differences in estimates of Earth's budgets and climate. Reconciling the different approaches remains a challenge. Only by using conservation and physical principles can we infer the likely resolution.

Recommended activities:

i) Improve accessibility and information content of products to evaluate the different components of EEI (ocean reanalysis products, in situ OHC, net flux at TOA, climate models) for use by wider community. Develop improved evaluation of these products to quantify strengths and weaknesses to provide advice to a wider range of potential users.
ii) Strengthen collaboration of interdisciplinary climate community by building up a synergy community. This requires funded collaboration initiatives (network funding for workshops, working visits at laboratories, etc.., e.g. started with ISSI working group, COST Action ES1402).
iii) Assessment of consistency between planetary heat balance and ocean heat storage as a multi-analysis approach from the synergy community to investigate uncertainties, quantify inconsistencies and understand their causes.
iv) Develop a community review paper on all components of EEI, or coordinate a special issue.

Appendix 3: Workshop participants

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approach
space
CAGE
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reanalysis
closure
fundamental
consistency
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